

Standard Model Higgs Searches at the Tevatron*

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We present the results of direct searches for the standard model Higgs boson at the Tevatron. Results are derived from the complete Tevatron Run II dataset, with a measured integrated luminosity of 10 fb^{-1} of proton-antiproton data. The searches are performed for assumed Higgs masses between 90 and 200 GeV/c^2 . We observe an excess of events in the data compared with the background predictions, which is most significant in the mass range between 115 and 135 GeV/c^2 , consistent with the Higgs-like particle recently observed by ATLAS and CMS. The largest local significance is 2.7 standard deviations, corresponding to a global significance of 2.2 standard deviations. We also combine separate searches for $H \rightarrow b\bar{b}$ and $H \rightarrow W^+W^-$, and find that the excess is concentrated in the $H \rightarrow b\bar{b}$ channel, although the results in the $H \rightarrow W^+W^-$ channel are still consistent with the possible presence of a low-mass Higgs boson.

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I. INTRODUCTION

The Higgs boson was hypothesised as a remnant of the Higgs field that was responsible for the electroweak symmetry breaking about a half century ago [1]. Understanding the mechanism for electroweak symmetry breaking, especially by testing for the presence or absence of the standard model (SM) Higgs boson, has been a major goal of particle physics and a central part of the Fermilab Tevatron physics program. Both CDF and D0 collaborations have performed new combinations of multiple direct searches for the standard model Higgs boson [2]. The new searches include more data, additional channels, and improved analyses techniques compared to previous analysis. Results are derived from the complete Tevatron Run II dataset, with a measured integrated luminosity of 10 fb^{-1} of proton-antiproton data. The searches are performed for assumed Higgs masses between 90 and 200 GeV/c^2 .

The global fit of the electroweak precision data, including recent top-quark and W boson mass measurements from the Tevatron [3, 4], constrains the Higgs mass m_H to be less than 152 GeV/c^2 at the 95% confidence level (CL) [5]. The direct searches from LEP [6], Tevatron [2], and LHC results [7, 8] set the Higgs mass between 116.6 and 119.4 GeV/c^2 or between 122.1 and 127 GeV/c^2 at the 95% CL. Recently both LHC experiments [9, 10] observed local excesses above the background expectations for a Higgs boson mass of approximately 125 GeV/c^2 . Much of the power of the LHC searches comes from $gg \rightarrow H$ production and Higgs boson decays to $\gamma\gamma$, W^+W^- , and Z^+Z^- , which probe the couplings of the Higgs boson to other bosons. In the allowed mass range, the Tevatron experiments are particularly sensitive to the association production of the Higgs boson with a weak vector boson in the $b\bar{b}$ channel, which probes the Higgs boson's couplings to b quarks.

The Tevatron collider produces proton and anti-proton collision at the center mass of 1.96 TeV with a record luminosity of $4.3 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. The Tevatron has delivered close to 12 fb^{-1} to each experiment before the shutdown on 30 September 2011 after 28 successful years running. Both CDF and D0 detectors are the general-purpose detectors, which provide excellent tracking, lepton identification, jets finding, and missing transverse energy (\cancel{E}_T) detections. The details can be found elsewhere [11, 12].

II. HIGGS PRODUCTION AND DECAYS

The dominant Higgs production processes at the Tevatron are the gluon-gluon fusion ($gg \rightarrow H$) and the associated production with a W or Z boson [13]. The cross section for the production of SM Higgs and its decays are summarized in Fig. 1 as a function of the Higgs mass between 100-200 GeV/c^2 . The cross section for WH production is twice that of ZH and is about a factor of 10 smaller than $gg \rightarrow H$. The Higgs boson decay branching fraction is dominated by $H \rightarrow b\bar{b}$ for the low-mass Higgs ($m_H < 135 \text{ GeV}/c^2$) and by $H \rightarrow W^+W^-$ or ZZ^* for the high-mass Higgs ($m_H > 135 \text{ GeV}/c^2$). A search for a low-mass Higgs boson in the $gg \rightarrow H \rightarrow b\bar{b}$ channel is extremely challenging because the $b\bar{b}$ QCD production rate is many orders of magnitude larger than the Higgs boson production rate. Requiring the leptonic decay of the associated W or Z boson greatly improves the expected signal over background ratio in these channels.

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As a result, the Higgs associated production with $H \rightarrow b\bar{b}$ is the most promising channel for the low-mass Higgs boson searches. For the high-mass Higgs, $H \rightarrow W^+W^-$ modes with leptonic decay provide the greatest sensitivity. The secondary channels of $H \rightarrow \gamma\gamma$, $H \rightarrow \tau^+\tau^-$, and $t\bar{t}H$ are also considered at the Tevatron. Finally, all the channels have to be combined to achieve the best SM Higgs sensitivity.

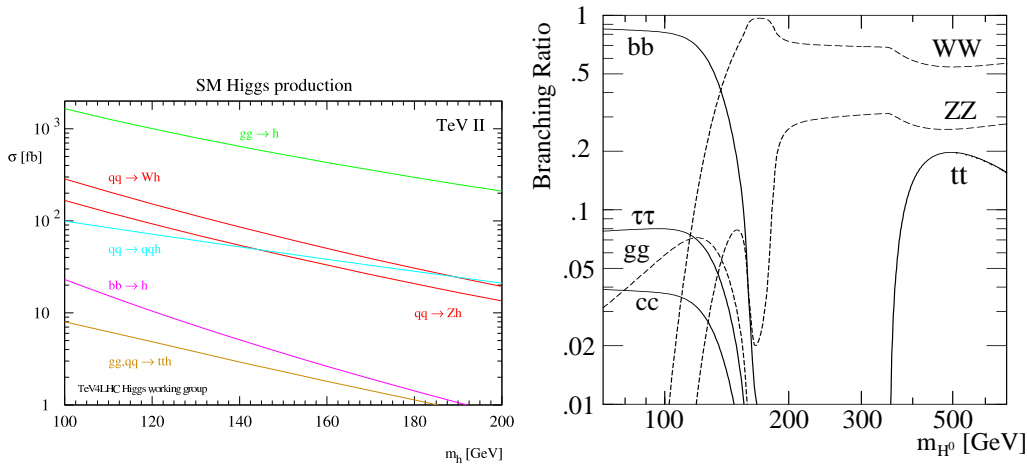


FIG. 1: SM Higgs production cross section at the Tevatron (left) and its decay branching ratio (right) as a function of the Higgs boson mass.

III. SEARCH STRATEGIES

The challenge for the standard model Higgs search at the Tevatron is that the Higgs signal is so tiny compared to that of other SM processes with the same final states. The search strategies employed by the CDF and D0 collaborations are quite similar and have been evolving constantly over time. We first maximize the signal acceptances by using efficient triggers, excellent lepton identifications, and powerful b -tagging, which can improve the signal to the background ratio up to the 1% level. Then we use multivariate analysis (MVA) to exploit the kinematic differences between the signal and background, which can further enhance the signal to the background ratio up to the 10% level in the high score regions. The same strategies have been used to help discover the single-top and diboson processes at the Tevatron, which provide a solid ground for how to isolate a small signal out of the huge background.

For the low-mass $H \rightarrow b\bar{b}$ signatures we look for a $b\bar{b}$ mass resonance produced in association with a W or Z boson where W decays into $l\nu$ or Z decays into l^+l^- or $\nu\bar{\nu}$. The $WH \rightarrow l\nu b\bar{b}$ is the most sensitive channel that gives one high P_T lepton, large \cancel{E}_T , and two b -jets. Before b -tagging, the sample is predominated by the W + light-flavor jets, which provides ideal control data to test the background modeling.

For the high-mass $H \rightarrow W^+W^-$ signatures, we look for the Higgs boson decaying into a W^+W^- pair in the inclusive Higgs events that lead to many interesting final states. The most sensitive channel is both W bosons decaying leptonically that gives an opposite-signed dilepton, large \cancel{E}_T , and some jets from the initial state radiation or other production processes. Because of the missed neutrinos in the final state, the Higgs mass can not be reconstructed. We have to rely on the event kinematic that distinguishes signal from background. For example, the $\Delta\phi$ of two leptons from the Higgs decay prefers a smaller $\Delta\phi$ than the background due to the fact that the Higgs is a scalar particle. We can further improve the separation between signal and background by combining the $\Delta\phi$ with other kinematic variables in the event using a multivariate discriminant.

IV. RECENT IMPROVEMENTS

Since there are two b -quark jets from the low-mass Higgs decay, improving b -tagging is crucial. Both CDF and D0 use MVA b -tagging to exploit the decay of long-lived B hadron as displaced tracks/vertices. The typical efficiency is about 40-70% with a mistag rate of 1-5% per jet. Recently CDF combined their existing b -taggers into a Higgs Optimized b -tagger (HOBIT) [14] using a neural network tagging algorithm, based on sets of kinematic variables sensitive to displaced decay vertices and tracks within jets with large transverse impact parameters relative to the

hard-scatter vertices. Using an operating point which gives an equivalent rate of false tags, the new algorithm improves upon previous b -tagging efficiencies by $\approx 20\%$. Fig. 2 shows the comparison of b -tag efficiency vs mistag rejection for the existing taggers and HOBIT b -tagger as shown in the black curve. The b -tag efficiency is calibrated using the $t\bar{t}$ events selected in the W + three or more jets sample and the b -enriched inclusive electron data, while the mistag rate is determined using the W + one jet sample. The ratio of b -tag efficiency per b -jet measured from the data and the Monte Carlo is used as a scale factor to correct for the differences in the Monte Carlo modeling,

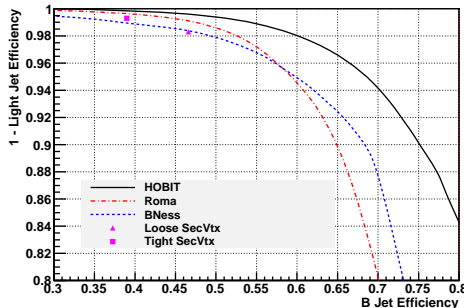


FIG. 2: A comparison of the purity-efficiency tradeoffs for HOBIT vs other b -taggers at CDF.

To discriminate Higgs signal events against background, using MVA would improve the background rejection with a sensitivity gain of 25%, compared to using a single variable alone, such as the dijet mass. We can further improve MVA by training different backgrounds, splitting events into sub-channels based on S/B, e.g. lepton type, number of jets. CDF trains $ZH \rightarrow l\nu b\bar{b}$ separately against $t\bar{t}$, $Z + c\bar{c}$ or c , and diboson to build the final discriminant.

V. LOW-MASS SEARCHES

We describe the searches for the low-mass Higgs boson at the Tevatron in some detail.

A. $WH \rightarrow l\nu b\bar{b}$

One of the golden channels for the low-mass Higgs boson search is the Higgs produced in association with a W boson with $WH \rightarrow l\nu b\bar{b}$ [15, 16]. We select events with one isolated high P_T lepton (electron, muon, or isolated track), a large missing transverse energy, and two or three jets, of which at least one is required to be b -tagged as containing a weakly-decaying B hadron. Events with more than one isolated lepton are rejected. For the multivariate discriminant, CDF trained a Bayesian neural network discriminant(BNN) in the W + two and three jets for each Higgs mass, separately for each lepton, jet multiplicity, b -tagging category. For the D0 $WH \rightarrow l\nu b\bar{b}$ analyses, the data are split by lepton type, jet multiplicity, and the number of b -tagged jets, similar to CDF. The outputs of boosted decision trees (BDT), trained separately for each sample and for each Higgs boson mass, are used as the final discriminating variables.

We perform a direct search for an excess of events in the signal region of the final discriminant from each event category. Fig. 3 shows the output of the final discriminants optimized for a 115 GeV/ c^2 Higgs signal in the double b -tagged W + two jets data from CDF and D0, respectively. The data and background predictions are in good agreement. The expected Higgs signals are also shown, but rescaled by a large factor.

Since there is no significant excess of signal observed in the data, we set an upper limit at 95% CL on the Higgs production cross section times branching ratio with respect to the SM predictions as a function of Higgs mass, as shown in Fig. 4. For $m_H = 125$ GeV/ c^2 , CDF set an observed (expected) upper limit at 4.9(2.8) while D0 set a limit at 6.2(4.8). They are not yet competitive for a single channel and we need to combine all other channels including both CDF and D0 results together.

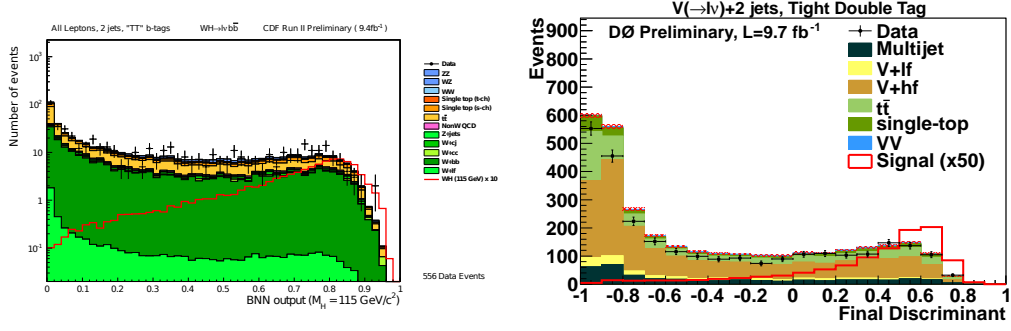


FIG. 3: The final discriminants for a 115 GeV/c² Higgs signal are shown in the $W + \text{two jets}$ after 2 b -tags for CDF's BNN (left) and DØ's BDT (right), respectively.

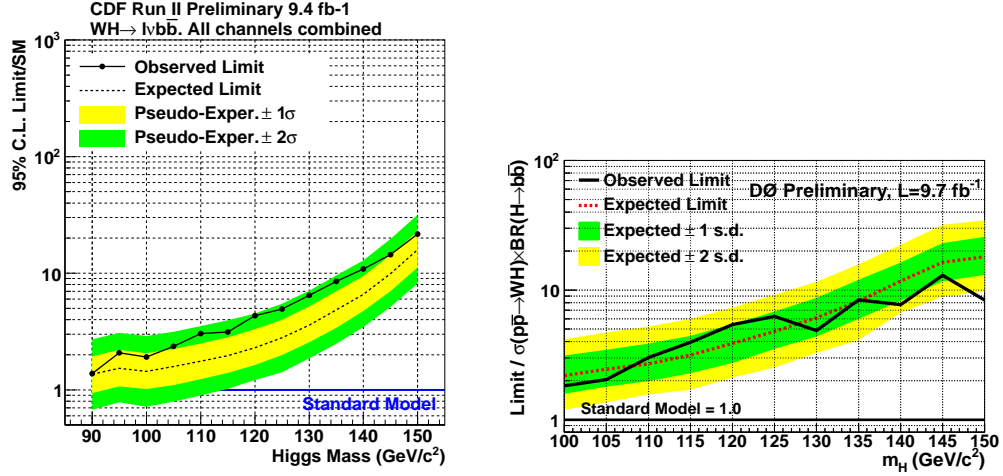


FIG. 4: Observed and expected 95% CL upper limits on SM Higgs production as a function of Higgs boson mass in the $WH \rightarrow l\nu b\bar{b}$ from CDF (left) and DØ (right), respectively.

B. $ZH \rightarrow l^+l^-b\bar{b}$

Another interesting channel to search for the low-mass Higgs boson is $ZH \rightarrow l^+l^-b\bar{b}$ [17, 18]. It provides a clean signature, but has a low event yield due to a small branching fraction of $Z \rightarrow e^+e^-$ and $\mu^+\mu^-$. We select events with two high P_T leptons from Z decay and two or three jets. Events are further divided based on lepton type, jet multiplicity, and the number of b -tagged jets, similar to $WH \rightarrow l\nu b\bar{b}$. To increase signal acceptance DØ loosens the selection criteria for one of the leptons to include an isolated track not reconstructed in the muon detector or an electron from the inter-cryostat region of the DØ calorimeter. CDF uses neural networks to select loose dielectron and dimuon candidates. DØ applies a kinematic fit to optimize reconstruction while CDF corrects jet energies for the missing E_T using a neural network approach. DØ uses random forests of decision trees to provide the final discriminant for sitting limits. CDF utilizes a multi-layer discriminant based on neural networks where separate discriminant functions are used to define four separate regions of the final discriminant function. Fig. 5 shows the final discriminant optimized for a Higgs signal ($m_H = 115$ GeV/c²) in the b -tagged events from CDF and the double b -tagged events from DØ, respectively. There seem to be some excess of events in the high score signal region, but not statistically significant yet. CDF set an observed (expected) upper limit at 95% CL on the Higgs cross section times branching ratio over the standard model prediction at 7.2(3.6) while DØ set a limit at 6.9(5.9) for the Higgs mass at 125 GeV/c².

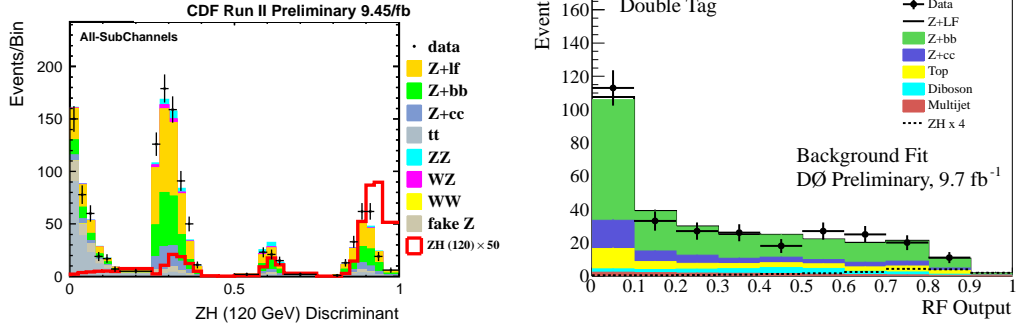


FIG. 5: The final discriminants are shown in the b -tagged Z + two or three jets events from CDF (NN output, left) and the double b -tagged Z + two jets events from DØ (RF output, right), respectively.

C. $WH, ZH \rightarrow \cancel{E}_T b\bar{b}$

We also looked for the Higgs boson in the ZH and WH channels where the Z decays into two neutrinos or the lepton from W decay is undetected [19, 20]. It has a large signal rate as well as a large QCD-multijet background. However, the final state is relatively clean, containing two high E_T jets and a large missing transverse energy. We require $\cancel{E}_T > 50$ GeV and two b -tagged jets. Both CDF and DØ use a track-based missing transverse momentum calculation as a discriminant against false \cancel{E}_T . In addition both CDF and DØ utilize multivariate technique, a neural network for CDF and a boosted decision tree for DØ, to further discriminate against the multi-jet background. The final discriminant is obtained for a Higgs signal ($m_H = 115$ GeV/ c^2) by combining dijet mass, track \cancel{E}_T , and other kinematic variables, which are shown in Fig. 6 for CDF and DØ, respectively. There seems a good agreement between data and background predictions, as CDF set an observed (expected) upper limit at 95% CL on the Higgs cross section times branching ratio over the standard model prediction at 6.8(3.6) while DØ set a limit at 3.8(4.3) for the Higgs mass at 125 GeV/ c^2 .

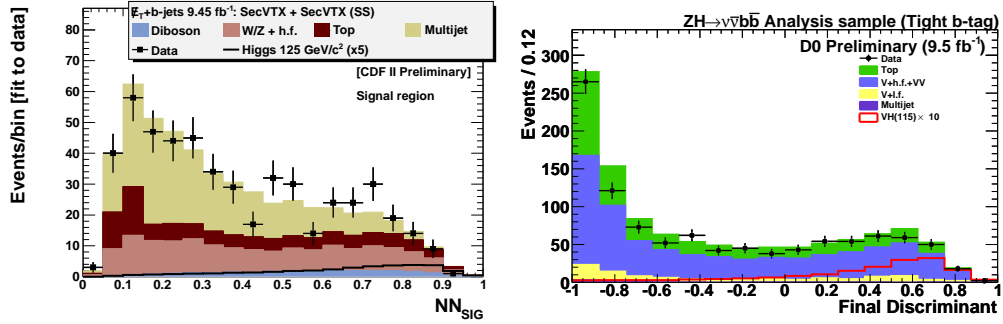


FIG. 6: The final discriminants are shown in the \cancel{E}_T + two jets after 2 b -tags for CDF (left) and after tight tag for DØ (right), respectively.

VI. HIGH-MASS SEARCHES

For the high-mass signatures, we look for Higgs decay into WW pair in the inclusive Higgs events that lead to many interesting final states [21, 22]. The most sensitive channel is both W decaying leptonic that gives an opposite-signed dilepton pair, large missing E_T , and some jets from the initial state radiation. The presence of neutrinos in the final state prevents the precise reconstruction of the Higgs boson mass. We have to rely on the event kinematic that distinguishes signal from background based on the scalar nature of the Higgs boson. We also include the processes $WH \rightarrow WW^+W^-$ and $ZH \rightarrow ZW^+W^-$ that give rise to like-sign dilepton and trilepton in the final states. Fig. 7 shows the $\Delta\phi$ distribution of two opposite-signed leptons in the zero jet bin. The red line is for the signal, which prefers a smaller $\Delta\phi$ than most backgrounds. By combining the $\Delta\phi$ with other kinematics we obtain a multivariate

discriminant shown in Fig. 7 that improves the analysis significantly. We set a 95% upper limit on the production cross section times branching ratio over the standard model prediction as a function of the tested Higgs mass after combining all $H \rightarrow W^+W^-$ channels including the low mass dileptons, the same sign, and trileptons from WH and ZH , as shown in Fig. 8. CDF observes some deficit near 165 GeV/ c^2 while D0 observes a broad excess, but they are consistent with each other.

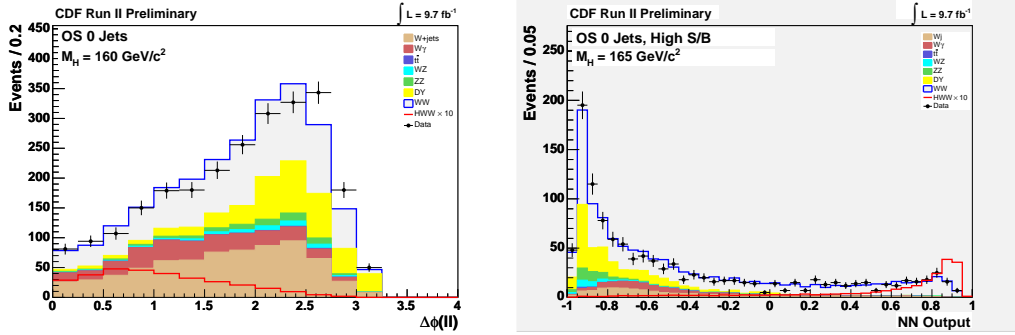


FIG. 7: The $\Delta\phi$ distribution of the two opposite-signed leptons in the events with no jets (left) and the final multivariate discriminant in right.

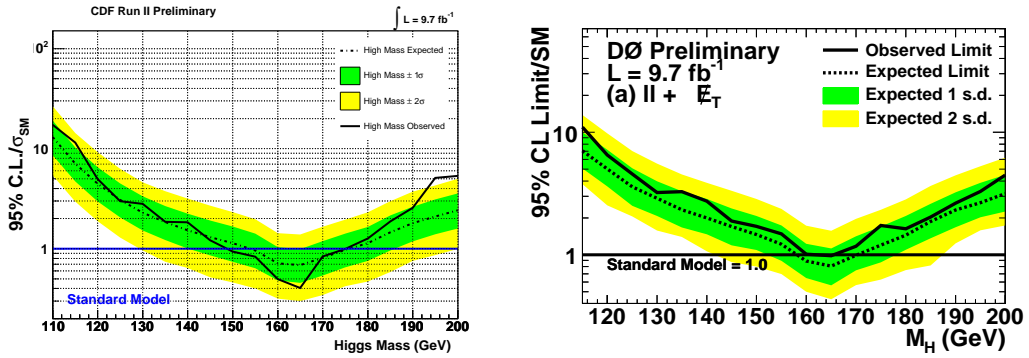


FIG. 8: Observed and expected 95% CL upper limits on SM Higgs production as a function of Higgs boson mass in the $H \rightarrow W^+W^-$ from CDF (left) and D0 (right), respectively.

VII. SECONDARY SEARCHES

Other searches are also considered for the $H \rightarrow \tau^+\tau^-$ decay [23, 24], the $H \rightarrow \gamma\gamma$ decay [25, 26], and the $t\bar{t}H$ production [27]. Fig. 9 shows their 95% CL upper limits on the production cross section times branching ratio with respect to the SM prediction, which is about a factor of ten larger than the SM Higgs sensitivity. But they do help to achieve the best Higgs sensitivity at the Tevatron.

VIII. TEVATRON COMBINATIONS

We have searched for all possible SM Higgs production and decays. and set limits with respect to nominal SM predictions. CDF and D0 are in good agreement and we combine them to improve the Tevatron final Higgs sensitivity.

To check the Tevatron Higgs sensitivity, we use the log-likelihood ratios (LLR) with different signal hypotheses to test the expected sensitivity as a function of Higgs mass, as shown in Fig 10. The black dot is for the background-only hypothesis, the red dot is for signal-plus-background hypothesis, and the solid curve is for the observed data. The colored bands indicate 1 or 2 sigma width of LLR for the background only distribution. The separation between the background only and the signal + background provides a measure of the search sensitivity, which is about 2 sigma for

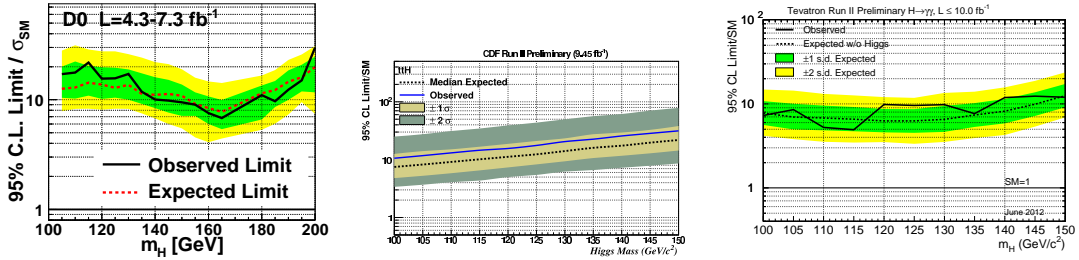


FIG. 9: The limits obtained from the searches on $H \rightarrow \tau^+\tau^-$ from D0 (left), $t\bar{t}H$ from CDF (middle), and $H \rightarrow \gamma\gamma$ from the Tevatron (left), respectively.

the Higgs boson mass at $125 \text{ GeV}/c^2$. The data seem consistent with the signal + background hypothesis between 115 and $135 \text{ GeV}/c^2$.

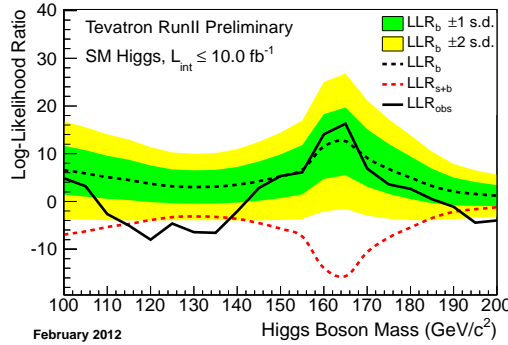


FIG. 10: The Tevatron combined LLR distributions as a function of Higgs mass.

All of the searches for the SM Higgs boson at the Tevatron are combined together for the best sensitivity [2]. We are able to exclude the Higgs mass between $100 < m_H < 106$ and $147 < m_H < 179 \text{ GeV}/c^2$ with comparable expected exclusion $100 < m_H < 120$ and $141 < m_H < 184 \text{ GeV}/c^2$, as shown in Fig 11. There are some excess of events observed in the mass range between 115 and $135 \text{ GeV}/c^2$ with a maximum local p-value of 2.7 standard deviations (sigma) at $m_H = 120 \text{ GeV}/c^2$, where the expected local p-value for a SM Higgs signal is 2.0 sigma. When corrected for the look-elsewhere effect (LEE), which accounts for the possibility of selecting the strongest of several random excesses in the range $115 < m_H < 200 \text{ GeV}/c^2$, the global significance of the excess is 2.2 sigma. We also combined results for different decay modes to see where the excess comes from. Fig. 12 shows the combined limit for $H \rightarrow b\bar{b}$ and $H \rightarrow W^+W^-$ separately. The observed limit in the $H \rightarrow b\bar{b}$ channel is more than 2 sigma higher than expected in the mass range between 115 - $135 \text{ GeV}/c^2$, which counts the majority of the excess in the same mass region.

Given the excess, we fitted the signal production cross section times branching ratio, normalized to the SM expectation, as a function of Higgs mass, as shown in Fig. 13. The obtained signal strength seems consistent with the SM Higgs signal in the mass range between 115 and $135 \text{ GeV}/c^2$.

To further check the compatibility with SM Higgs signal at $m_H = 125 \text{ GeV}/c^2$, we compared the LLR by injecting the Higgs signal of $m_H = 125 \text{ GeV}/c^2$ into the background-only pseudo-experiment (shown in Fig. 14) which seems consistent with the LLR observed in the data as shown in Fig. 10. The distribution is quite broad due to the fact that the final discriminant is not optimized for mass, but for the signal and background separation.

Finally, it's worth noting that the Tevatron has made significant progresses to achieve the SM Higgs sensitivity. The gain obtained over time seems go proportional to the inverse of the extra luminosity used, instead of the square root of the luminosity.

IX. CONCLUSION

In clusion, with a full dataset and many years of hard work, the Tevatron has finally achieved the SM Higgs sensitivity over most of the mass range up to $185 \text{ GeV}/c^2$. We observe an excess of events in the data compared

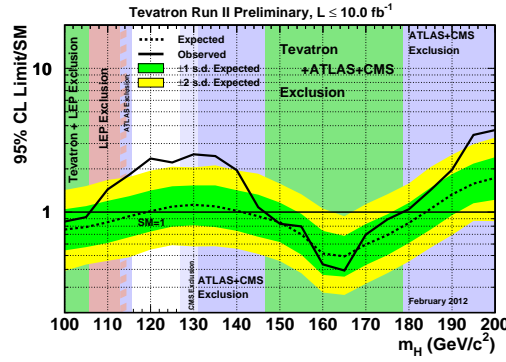


FIG. 11: The Tevatron combined Higgs limit as a function of tested Higgs mass.

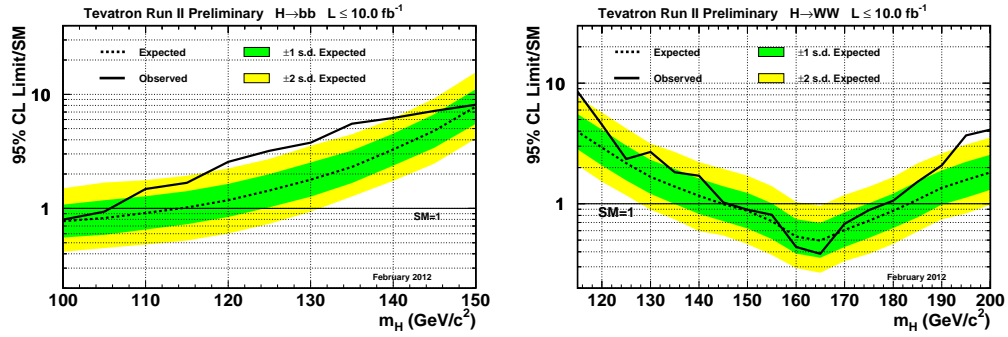


FIG. 12: The Tevatron combined Higgs limit as a function of tested Higgs mass in the $H \rightarrow b\bar{b}$ (left) and $H \rightarrow W^+W^-$ (right) decays separately.

with the background predictions, which is most significant in the mass range between 115 and 135 GeV/c^2 , consistent with the Higgs-like particle recently observed by ATLAS and CMS. The largest local significance is 2.7 standard deviations, corresponding to a global significance of 2.2 standard deviations. We also combine separate searches for $H \rightarrow b\bar{b}$ and $H \rightarrow W^+W^-$, and find that the excess is concentrated in the $H \rightarrow b\bar{b}$ channel, although the results in the $H \rightarrow W^+W^-$ channel are still consistent with the possible presence of a low-mass Higgs boson.

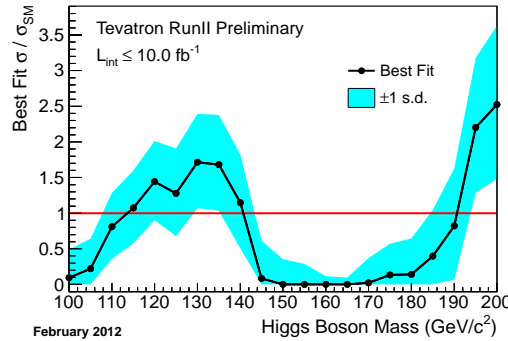


FIG. 13: The fitted signal strength as a function of the Higgs mass, which the data seem consistent with the SM Higgs signal in the mass range between 115 and 135 GeV/c^2 .

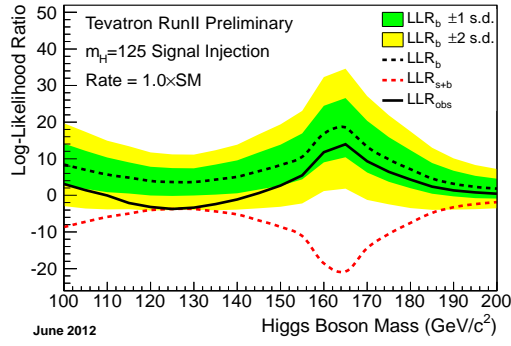


FIG. 14: The expected LLR after injecting an SM Higgs signal at $m_H = 125 \text{ GeV}/c^2$ into the background-only-pseudo experiment.

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